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SERVICE LIFE INVESTIGATIONS FOR AGING AIRCRAFT

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INTRODUCTION

The report is the reply to EOARD proposal.

In May 1997 a report was sent to EOARD that consisted of two parts. Part I contained the information about all principal TsAGI investigations dealing with aircraft structural strength. Part II presented the study of aging aircraft fatigue and damage tolerance. This report is the final one upon EOARD proposal. It contains the summary of results received in the studies presented in Part II of the previous report. This report outlines residual strength criteria for the structures having widespread fatigue damage and gives the results of investigation into corrosion damage of aircraft structures.

FATIGUE AND DAMAGE TOLERANCE OF AGING AIRCRAFT STRUCTURES

G.I.Nesterenko*

Principles to be followed in certification testing the airframe components for fatigue resistance and damage tolerance are outlined. Criteria for estimating residual strength of full-scale structures with wide-spread fatigue damage are formulated. Rates of multi-site damage growth in new and ageing airplane structures are compared. Corrosion development data are provided.

INTRODUCTION

One of the most important problems in aviation is the one of ensuring safe operation of aging aircraft. Up to date many Russian aircraft types have worked out their design service lives. It is impossible to replace all of old aircraft types by newer ones in the nearest future, so it seems obligatory to prolong service lives and durability of aging aircraft beyond the design goals. This requires testing the long-operated aircraft for fatigue resistance, ensuring damage tolerance of the structures with widespread fatigue damage (WFD), studying the degradation of crack resistance and fatigue strength after long-term operation, and ensuring safe operation of corrosion-damaged structures. This paper outlines the experience of dealing with the above problems in Russia.

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CONCEPTS FOR SPECIFYING ALLOWABLE SERVICE DURATION

Standard approaches to specifying aircraft service life in the USSR and in Russia are presented in the paper by Raikher et al. (1). In 1950s through 1970s the USSR Civil aircraft airworthiness standards contained the only concept to ensure long-term aircraft safety named safe life concept. In 1976 alongside with the safe life concept the other concept called damage tolerance has been introduced as having equal rights. The USSR aviation utilized the concept based on "operational survivability" including both damage tolerance and fail-safe concepts. In 1994 Aviation Regulations AP 25.571 for transports have been introduced where the concept of operational survivability is stipulated as the principal one.

Every aircraft type in the USSR was required to undergo full-scale structure fatigue-resistance and damage tolerance tests. These were conducted up to reaching at least three design service lives. High-time structures of every aircraft type were also tested. In many cases several structures of a particular type were tested.

In parallel with the tests the fatigue resistance, crack growth rate and residual strength of the structures were calculated. Test and analytical results were then correlated with fleet data on structural damage. The comprehensive studies provided the values of service lives, inspection intervals, and structural component repair/replacement deadlines.

The today's activity is to prolong service lives and durability of Antonov, Ilyushin, Tupolev and Yakovlev aging airplanes. The service lives of these airplanes are planned to become 1.5 times the design goals. Appropriate activities have been prepared for each aging aircraft type as well as for major operation categories common to all aircraft types. Service lives of aging aircraft may be prolonged individually.

WIDESPREAD FATIGUE DAMAGES

The problem of widespread fatigue damage (WFD) including multi-site damage (MSD) and multi-element damage (MED) first arose in the USSR after the 1972 accident with an Antonov An-10 passenger airplane. The relevant studies are reviewed in Nesterenko (2), (3) and (4). The problem solution was based on experimental evaluation of crack growth duration and residual strength of various full-scale structures with WFD. Fatigue crack growth curves for the structures having WFD were generated upon fractographic analyses. WFD in some aircraft types was

detected not only during the tests but also in operation. In the latter case crack growth curves were derived by mathematical statistics methods.

Widespread fatigue damage initiates in the primary structural sections where a great number of stress concentrators and components with almost identical fatigue life values are located. Full-scale structure fracture analyses showed that the structure with WFD becomes critical at the moment of fatigue crack initiation in approximately 50 per cent of the components or stress concentrators having equal endurance. Fatigue cracks differ in size. It is frequent that there appear several cracks larger than others. In this case the leading crack seems difficult to identify. It is reasonable to regard as WFD threshold the moment of initiation of two fatigue cracks.

Residual Strength

Test data analysis has shown that the residual strength of the structures with WFD is affected by numerous factors. In many thin sheets MSD appears on smooth surfaces rather than at holes as expected. References (2) and (3) demonstrate different WFD types revealed in airframes. Figure 1 presents MSD types detected in the riveted longitudinal splices of skin sheets in pressurized fuselages.

The experimental and analytical study of residual strength of the structures with WFD is carried out allowing for stable crack growth under static loading. Several full-scale aircraft structures with clearly seen MSD have undergone residual strength certification tests. For these tests special foil-based sensors were bonded to the skin at the distance of 3 to 5 mm from crack tips. The sensors were connected to the aircraft loading control system. The growing static load developed the cracks. Should any sensor be broken, the structure loading system was switched off.

Reference (4) suggests one of the residual strength criteria for analysing the structures with WFD, taking into account stable crack growth. The residual strength criterion for thin-wall structures with WFD may be formulated as follows: net stresses in the section with cracks are equal to yield strength, $\sigma_{0.2}$. These stresses are calculated taking into account stable crack growth. Using this criterion requires some test data similar to those presented in Fig. 2.

Table 1 provides the residual strength data for structures with WFD. Most of these data are given in Refs (2) and (3). Apparent fracture net stresses $\sigma^{app}_{fr.net}$ were determined considering the decrease in cross section

TABLE 1 - Residual strength of full-scale aircraft structures with widespread fatigue damages:

Damaged principal structural element	Material	$\frac{\sigma^{app}_{fr.net}}{\sigma_{0.2}}$	$\frac{\sigma^{c}_{fr.net}}{\sigma_{0.2}}$	$\frac{K_{fr}}{K_{app}}$	$\frac{K_{fr}}{K_{Ic}}$
Skin and stringers near stringer splice in wing lower surface	D16ATN D16T	0.8	1.0	0.5	-
Skin and stringers of lower wing surface around stiffening lap edges	D16AT D16T	0.9	1.0	0.5	-
Skin and stringers of monolithic stiffened panel of lower wing surface near fuel holes in stringer	D16T	0.7	0.83	1.0	-
Spars and shapes of upper wing surface	D16T	0.3	0.47	0.5	-
Splice shapes of upper wing surface	D16T	0.7	1.0	0.75	-
Stringer and lap for circumferential skin splice of pressurized fuselage	D16AT D16T	0.75	0.88	1.0	-
Pressurized fuselage skin near three-row longitudinal riveted splice	D16AT	0.57	1.0	0.5	-
Pressurized fuselage skin near two-row longitudinal riveted splice	D16AT	0.63	1.05	0.9	-
Pressurized fuselage skin near two-row longitudinal riveted splice	D16AT	0.48	0.85	0.7	-
Strip joining the cylindrical pressurized fuselage with spherical pressure bulkhead	D16AT	0.16	0.17	0.45	-
Skin and stringer of lower wing surface around stiffening lap edges	V95AT1 V95T1	0.45	0.46	1.0	-
Lap joining the skins of lower wing surface	V95AT1	0.4	0.41	0.4	1.0
Wing pivot assembly	V93T1	0.4	0.4	-	1.0

areas of primary elements due to hole and initial cracks. When calculating critical fracture stresses $\sigma^{c}_{fr.net}$, additional attention was paid to section weakening due to stable crack growth, see Fig. 2. The above mentioned stresses were compared to the yield strength $\sigma_{0.2}$. The stress intensity factor K_{fr} for final structure fracture has been calculated using approved methods. These factors were compared to plane strain fracture toughness K_{Ic} or to apparent plane stress fracture toughness K_{app} that was found in experiments on sheets with no bulging elimination devices.It follows from Table 1 that residual strength criteria for structures made of brittle materials like V95T1 and V93T1 are the linear fracture mechanics criteria $K_{fr} = K_{app}$ or $K_{fr} = K_{Ic}$. For many structures made of plastic materials like D16T and having WFD with interacting cracks the residual strength criterion may be formulated as follows: the stresses calculated considering stable crack growth are equal to yield strength, $\sigma^{c}_{fr.net} = \sigma_{0.2}$. Some structures were broken when $\sigma^{c}_{fr.net} < \sigma_{0.2}$; this can be accounted for by the effect of local bending stresses difficult to evaluate. For a structure out of D16T alloy having several cracks in a single plane that have no interaction the residual strength criterion is, obviously, $K_{fr} = K_{app}$.

Crack Growth Duration

The most important test data on fatigue crack growth duration for full-scale airplane structures with WFD are presented in Ref. (3). Figures 3, 4, 5 and 6 provide additional test data. Figures 5 and 6 compare these data with the in-service crack growth data. A fractography methodology was developed, and crack growth curves on the basis of structural tests were generated, by Stoyda and Yekimenkov (5). A methodology for analysing the cracks detected in the course of aircraft inspection was developed by Senik (6); it is based on mathematical statistics; also, in-service crack growth curves have been generated.

In Figs 3 through 6 the relative value of operational time T is the ratio of a current operational time to the time when the structure with WFD fails during the tests. Fleet data are reflected by the points presenting crack sizes and flight numbers of those airplanes where WFD was detected. These data have been the basis for crack growth duration curves corresponding to the probability P of 0.5, 0.05 and 0.001.

The analysis of data presented in Figs 3 through 6 and in Ref. (3) has shown that the ratio of crack growth time ΔT to the total life (equal to the time period before crack initiation, T_0, plus crack growth duration) may range widely: $\Delta T/T_0 + \Delta T = 0.03 - 0.8$. It also follows from the analysis that defining inspection intervals for structures with likely WFD should be based on safety factors of 2 to 3, as related to the mean values of in-service multi-site crack growth duration.

When designing modern structures, some measures are taken to avoid in-service WFD initiation.

CRACK RESISTANCE AND FATIGUE STRENGTH DEGRADATION

Reference (4) compares test data on fatigue lives of new airplanes and the high-time airplanes, as well as compares wing skin materials crack resistance for some of these airplanes. Experiments showed that operational factors decrease structural fatigue strength. Wing skin crack resistance after long-term operation appeared less than crack resistance of the same alloys manufactured later. One of the reasons therefor may be the increased silicon and iron fraction in the D16T and V95T1 alloys utilized to fabricate the structures tested. Test data presented in Figs 5 and 6 also demonstrate that high-time structures show earlier initiation of multi-site cracks and higher growth rate than in test of new structures.

It should be noted that structures of currently designed Russian airplanes would be made from 1163T, V95ochT2, and 1933T3 alloys with less silicon and iron and improved fabrication techniques, instead of the D16T, V95T1 and V93T1 alloys, respectively.

CORROSION

The problem of ensuring safe operation of aircraft structures having corrosion-induced damages is being solved on the basis of fleet experience. Stiffened structures of the wing, fuselage and tail are inspected to detect corrosion during aircraft maintenance after 300, 600, 900, and 1800 flight hours, and 5 years of usage. As for aluminum structures, when corrosion depth is in the range of 10 to 15 per cent of the initial element thickness, the defect is eliminated by grinding. When corrosion is deeper the elements are repaired. In the areas likely to corrode it is recommended that standardized residual strength is ensured for the structure with standardized damages - a two-bay skin crack with a stringer or frame broken, in the form of fracture in a separate primary element. Following the instructions on structural inspection and repair ensures safe aircraft operation in the case of corrosion-induced damage.

When the most dangerous type, the stress corrosion, is found in the principal structural elements, and in the case of various corrosion types in steel structures having one-path load transfer, then corrosion damage growth rates are determined from fleet data. Here, the same mathematical statistics methodology is used as in fatigue crack growth duration calculation by (6). Critical sizes of the damage are established by proceeding from $\sigma_{0.2}$ or K_{Ic} criteria.

Figures 7 through 10 present the data on in-service corrosion damage growth. These data are utilized to prescribe inspection and repair intervals for relevant structures.

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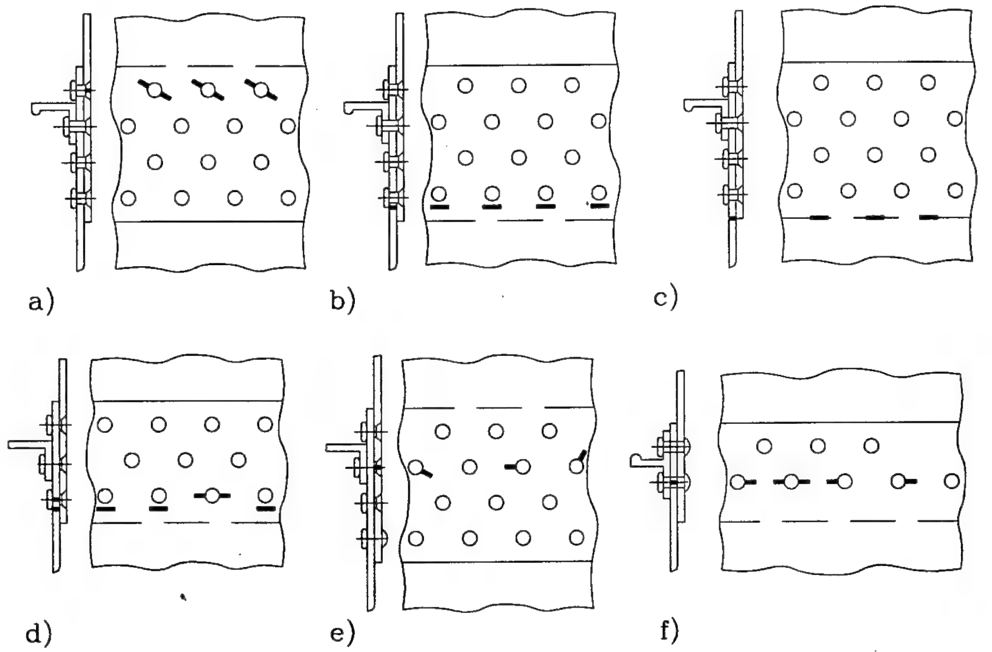

Figure 1 Multi-site skin damage of full-scale pressurized fuselages

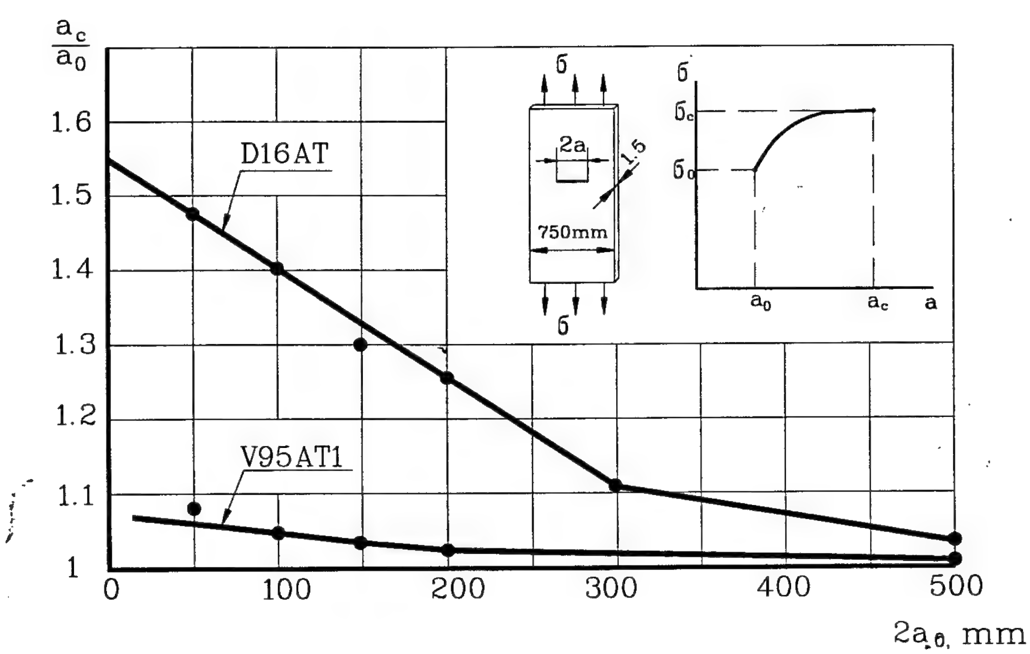

Figure 2 Stable crack growth from sheet cutouts

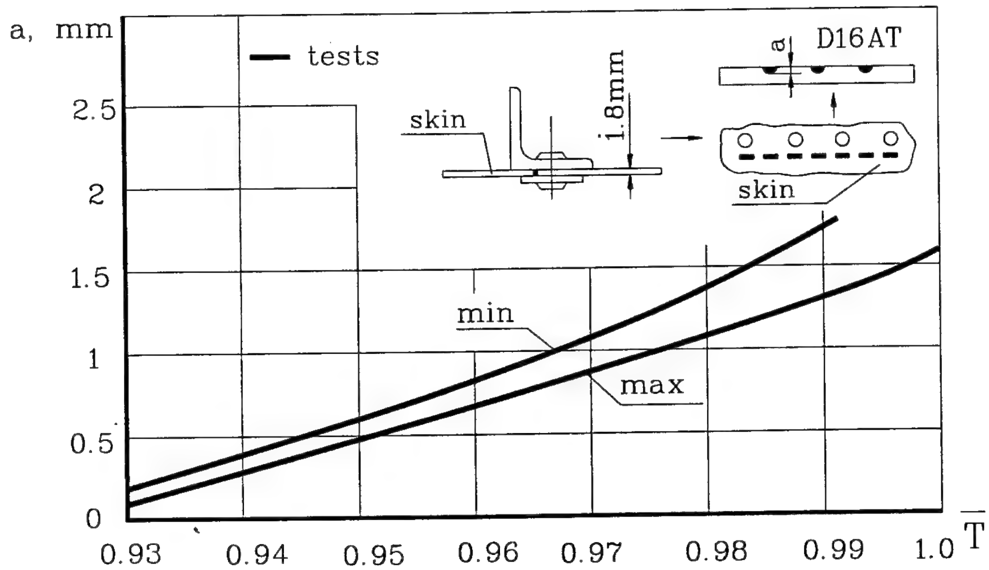

Figure 3 Relative MSD growth time: horizontal panel of pressurized fuselage

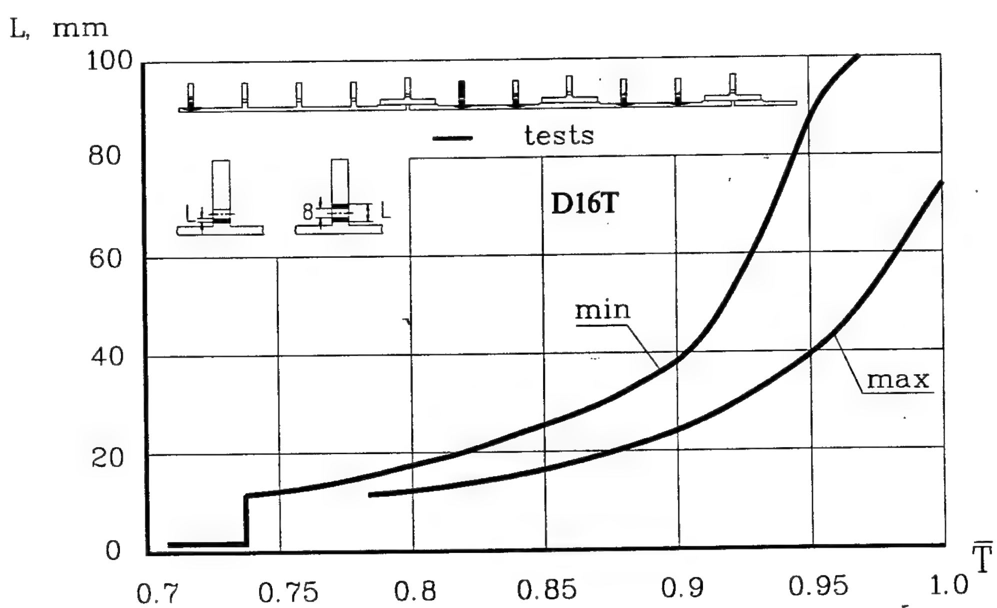

Figure 4 Relative MED growth evolution time: wing panels

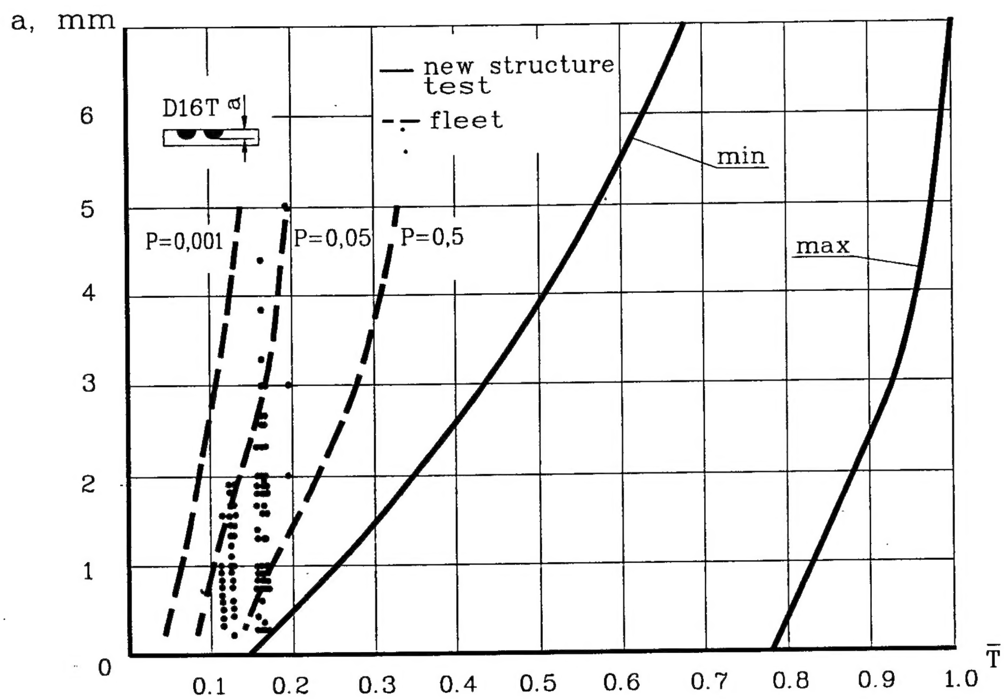

Figure 5 Relative MSD growth time: upper wing panel attachments

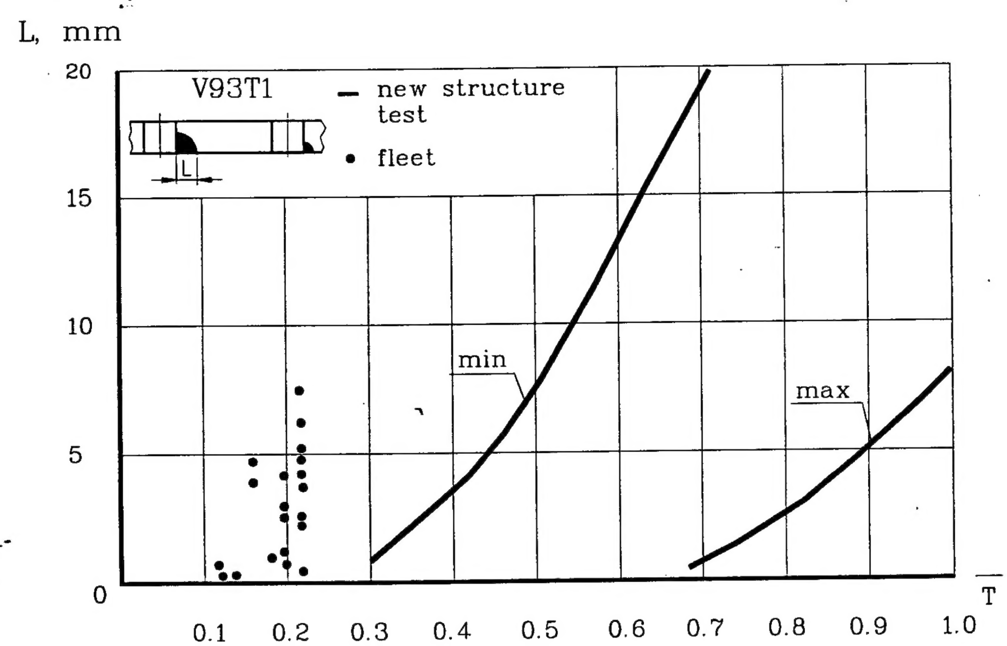

Figure 6 Relative MSD growth time: lower wing panel attachments

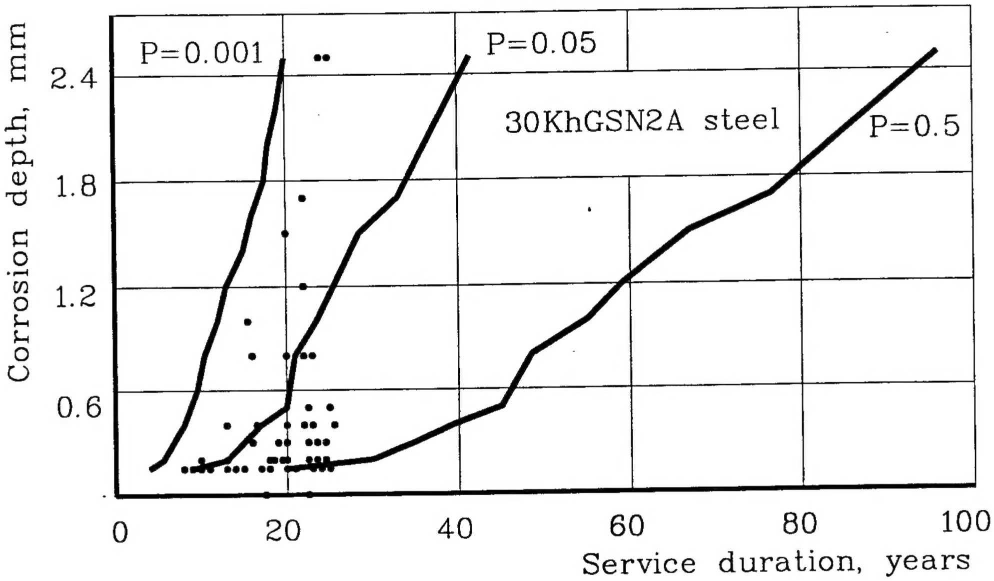

Figure 7 Corrosion propagation in engine frame strut

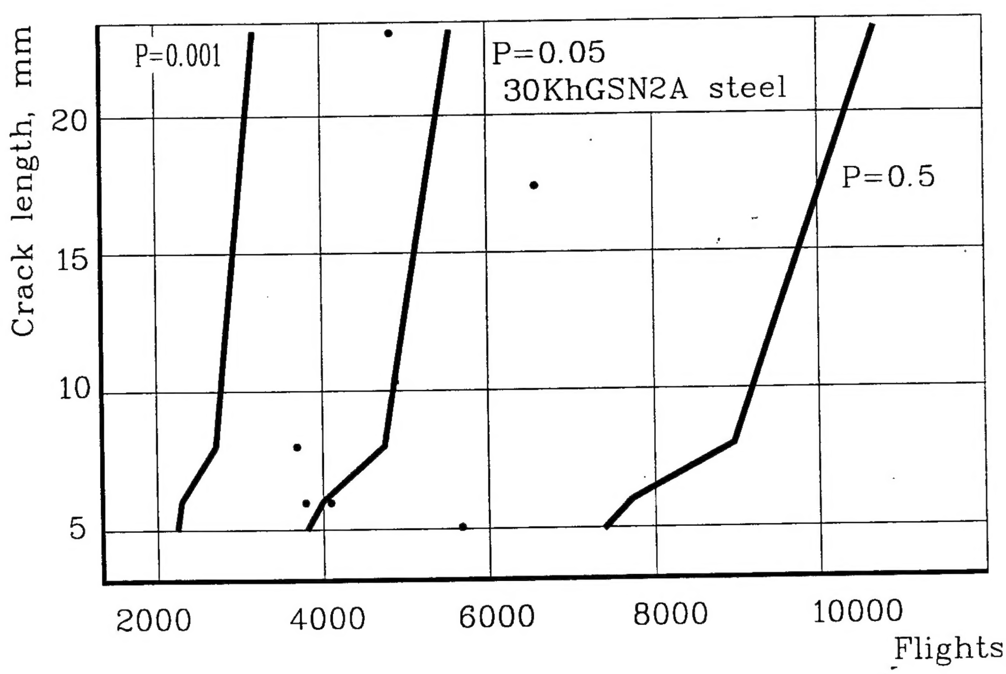

Figure 8 Corrosion-fatigue damage growth in landing gear cylinder

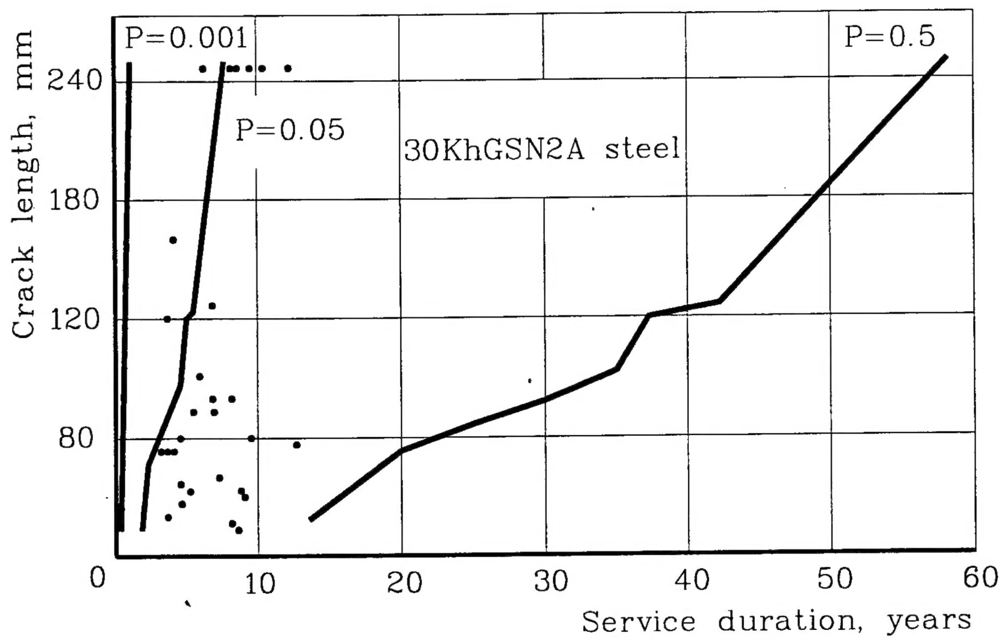

Figure 9 Stress corrosion development: landing gear unit

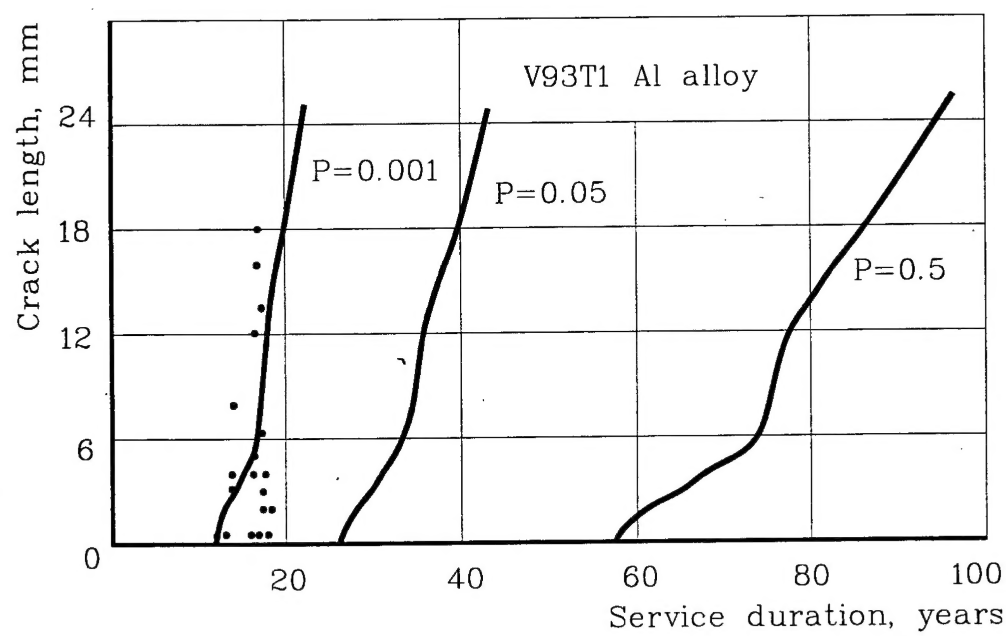

Figure 10 Stress corrosion development: flap attachment bracket

CONCLUSION

- Residual strength criteria for structures with WFD are $\sigma^{c}_{fr.\,net} = \sigma_{0.2}$., K_{app}, K_{Ic}.
- Aging structures exhibit crack and fatigue resistance degradation.
- Corrosion growth rate can only be assessed properly on fleet data basis.